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MICROSTRUCTURAL EFFECT ON THE RESISTIVITY OF THIN SILVER FILMS

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13. ABSTRACT (Maximum 200 words)

Thin silver films were deposited using the partially ionized beam deposition technique. It was found that the resistivity of the films is strongly dependent on the incident ion energy used during film growth. The observed resistivity trend exhibits a minimum that is near the bulk value for silver. The x-ray fiber texture analysis technique was used to determine the microstructure of the films. The change in resistivity is shown to be correlated with film microstructure through the change in the fraction of grains whose surface normals are oriented randomly with respect to the substrate normal. The electronic grain boundary reflection coefficient, as extracted from the model of Mayadas and Shatzkes, is shown to also vary with the microstructure.

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INTRODUCTION

Current trends in the microelectronics industry have increased the importance of low resistance interconnect metals. As device structures become smaller and faster, the interconnect signal delay will soon dominate the device performance. Attempts to reduce this delay have been twofold: the reduction of the dielectric constant of the insulating material, and the reduction in the resistivity of the metal interconnect wires. However, there are other problems associated with reduction of interconnect line dimensions. As line widths become smaller, the line current density increases, increasing the risk of electromigration behavior in the film. Thus, the search for a lower resistivity interconnect must be coupled with a means to control the onset of electromigration as well.

Recent work has shown that the orientation of the grains can play a large role in the film properties. Several researchers have been able to show a link between the microstructure and mean time-to-failure rates in thin film conductor lines. This report describes the relationship between the microstructure and the resistivity of thin silver films. Several factors can affect the resistivity of a thin film. For films of high purity, the average grain size is typically considered to be the most important parameter. It is found that a decrease in the volume fraction of grains oriented with a random distribution correlates well with a decrease in the film resistivity.

EXPERIMENTAL PROCEDURE

Using the partially ionized beam (PIB) deposition technique, thin silver films were deposited on glass substrates. The PIB technique has been described in a previous paper (ref 1), and has been shown to be capable of controlling the grain orientation in thin films (refs 2,3). In essence, the PIB utilizes ions derived from the vapor stream (self-ions) to increase the energy at the growth front of the deposited film. The percentage of ions striking the film surface in this fashion can be varied between 0.1 and 5 percent of the neutral flux, and the energy of the incident ions can be varied between 0 and 3.5 KeV. In this study, the glass substrates were held at room temperature during the deposition. To prevent charging of the substrates, an oscillating bias voltage of 1 KHz was applied to the substrate, allowing stray electrons to strike the growth front (ref 4). A deposition rate of approximately 3 Å/s was used. The thickness of the films was approximately 2000 Å. This thickness was chosen as it is well above the mean free path of an electron in bulk silver (540 Å) (ref 5).

Resistivity measurements were performed using a standard four-point probe technique on the metal films deposited on glass. Thickness measurements via a Tencor Alpha Step were used to convert the sheet resistance measurements to resistivity. The circular points in Figure 1 show the variation of the resistivity of the silver films as a function of ion energy used during the deposition of the films.

The solid line in Figure 1 is a plot of the resistivity using the model of Mayadas and Shatzkes (MS) (ref 6). The MS model relates the resistivity in a thin film with the single-crystalline resistivity by the equation

1

$$\frac{\rho_0}{\rho_g} = 1 - \frac{3}{2}\alpha + 3\alpha^2 - 3\alpha \ln(1 + \frac{1}{\alpha}) \tag{1}$$

where ρ_g is the grain boundary resistivity, ρ_o is the single-crystalline resistivity of the material, and α is the resistivity parameter given by

$$\alpha = \frac{l}{d}\frac{R}{1-R} \tag{2}$$

where l is the intrinsic electronic mean free path, d is the average grain size in the film, and R is the grain boundary reflection coefficient, which is usually considered to be a constant.

One of the benefits of using the PIB technique is that the orientation of the films can be changed, while keeping the grain size relatively constant. The average grain size of the silver films was determined by measuring the broadening of the x-ray 2θ signal. The grain sizes of the films were found to be between 920 and 1200 Å, with the exception of the 1.3 KeV deposition, which had an average grain size of about 400 Å. The difference in the grain size for this film could be due to the larger deposition rate, 28 Å/s, used.

OBSERVATIONS

For PIB copper films, it has been shown, using secondary ion mass spectroscopy, that oxygen is the only significant impurity (refs 7,8). Oxygen is known to increase the resistivity of metals about 1 $\mu\Omega\cdot$cm per atomic percent (ref 9). The oxygen content in the PIB copper films was found to be about 5.9×10^{-3} atomic percent near the optimum ion energy. Recent modeling of the PIB process has shown that silver and copper should behave similarly in our system (ref 10).

Using Eq. (1) and inserting the average grain size values and electronic mean free path (540 Å) for the silver films, a theoretical value for the resistivity due to the grain size was found. The reflection coefficient used in the calculation was that for copper, R = 0.24 (ref 6). The reason for this choice was due to the lack of data in the literature for a silver reflection coefficient. Differences in this value may shift the calculations, however the general line shape will not change. Adding to this approximately 0.006 $\mu\Omega\cdot$cm for impurities, an expected value for the resistivity can be calculated, represented by the sold line in Figure 1. The increase in the resistivity in the calculation at an ion energy of 1.3 KeV follows that of experiment due to the smaller grain size. Even should the impurity concentration in the silver films be an order of magnitude higher than that found in copper, this would still mean an increase in resistivity of approximately 0.01 $\mu\Omega\cdot$cm, a change which is an order of magnitude smaller than evidenced in the

experimental data. As can be seen, impurity and grain size effects cannot account for the existence of a minima in the resistivity.

The resistivity effect may be explained be examining the microstructure in the films. The microstructure of the films was examined using a subset of the x-ray pole figure technique, the fiber texture plot. A Scintag XDS2000 operated in the Schultz reflection geometry was used. From the fiber texture data, it was possible to determine the volume fraction of grains whose <111> planes were oriented with the substrate surface, as well as the volume fraction of grains oriented in a purely random fashion. The <200> volume fraction could not be measured due to the low x-ray intensity of this reflection in the films. Thus, in our films, the random volume fraction was the complement of the <111> volume fraction. Figure 2 plots the resistivity and random volume fraction as a function of the ion energy. While the volume of the <111> orientation changes between films, the width of the distribution as given by the angle at which intensity has fallen to within 10 percent of the peak, ω_{90}, remains relatively constant; ω_{90} varies by less than 10 percent, the average being 21°. As can be seen, there is a very strong correlation between the decrease in random volume fraction and the decrease in resistivity, the minima of both quantities occurring at the same energy. Thus, it appears that the PIB technique is able to produce very low resistivity by affecting the film microstructure via the bombardment of ions during the growth phase of the film.

It is possible to explain this change in the resistivity by examining the theoretical underpinnings of the MS model. The original model makes the assumption that all of the grains in the films are oriented such that the grain boundary normals lie in the film plane. As is seen by the texture analysis of our films, this is not, in general, true. Only those films with very high texture, or very low random volume fractions, will approach the ideal of Mayadas and Shatzkes. Table 1 is a tabulation of the reflection coefficients made by fitting the MS model to the data with R as a free parameter. Parmigiani et al. (ref 11) give evidence that R is not constant; however in their study, the films contain significant void fractions and the more subtle effects of the microstructure, such as texture, which are relevant to films of industrial quality, are masked.

It is apparent from the table that the lowest value of the reflection coefficient coincides with the lowest random volume fraction. The random volume fraction is a measure of grains that are found to be in a purely random distribution in the film. Thus, a decrease in this value indicates there is a decrease in the likelihood that two neighboring grains will have uncorrelated orientations. Because of this, if the grain-to-grain misorientation angle were averaged throughout the film, the result would be lower for those films with a smaller random volume fraction. Calling the average of the grain-grain misorientation angle the average grain tilt, the average reflection coefficient is seen to increase with the tilt of the grain boundary from perpendicular. If the grain boundary potential is assumed to be a delta function potential (i.e., $V(x) = S\delta(x - x_n)$ for the nth boundary), the potential strength, S, can be related to the reflection coefficient by

3

$$\frac{m}{h^3 d} \frac{S^3}{k_F} 2\tau = \frac{l}{d} \frac{R}{1-R} \qquad (3)$$

where m is the electron mass, k_F is the magnitude of the Fermi wave vector, and τ is the relaxation time constant for scattering from point defects and phonons (ref 6). Using this relation, it can be argued that grain boundary tilt increases the relative strength of the boundary potential, S. This makes good intuitive sense in that as the grain boundaries become more randomly oriented with respect to one another, the lattice distortion between neighboring grains should also increase. This increase in lattice distortion becomes evident in the potential strength parameter, S, which in turn causes an increase in the grain boundary reflection coefficient, R.

CONCLUSION

In conclusion we have shown that the PIB technique can be used to grow thin silver films with bulk-like resistivities at room temperatures. We believe that the reason for the improved resistivity is that the ion-assisted deposition changes the microstructure of the films towards a highly oriented grain texture. By changing the grain orientation in this way, the electronic reflection coefficient at the grain boundaries is lowered, and, hence, the resistivity is improved.

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**Table 1. Reflection Coefficient Values Calculated as a Free Parameter
Fit of the MS Model to the Experimental Data**

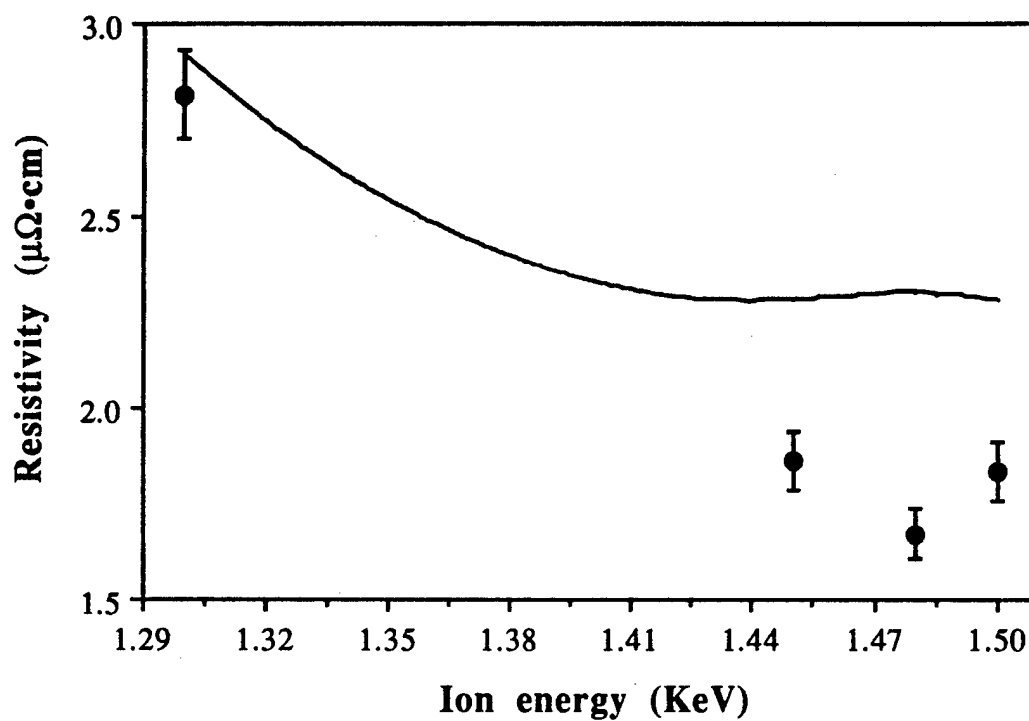| Ion Energy (eV)	Random Volume Fraction	Reflection Coefficient
1300	0.95	0.296
1450	0.85	0.196
1480	0.79	0.071
1500	0.82	0.175

Figure 1. Resistivity of PIB silver films as a function of the ion energy used during deposition. The solid line is the theoretical prediction of the resistivity using the model of Mayadas and Shatzkes and correcting for impurities.
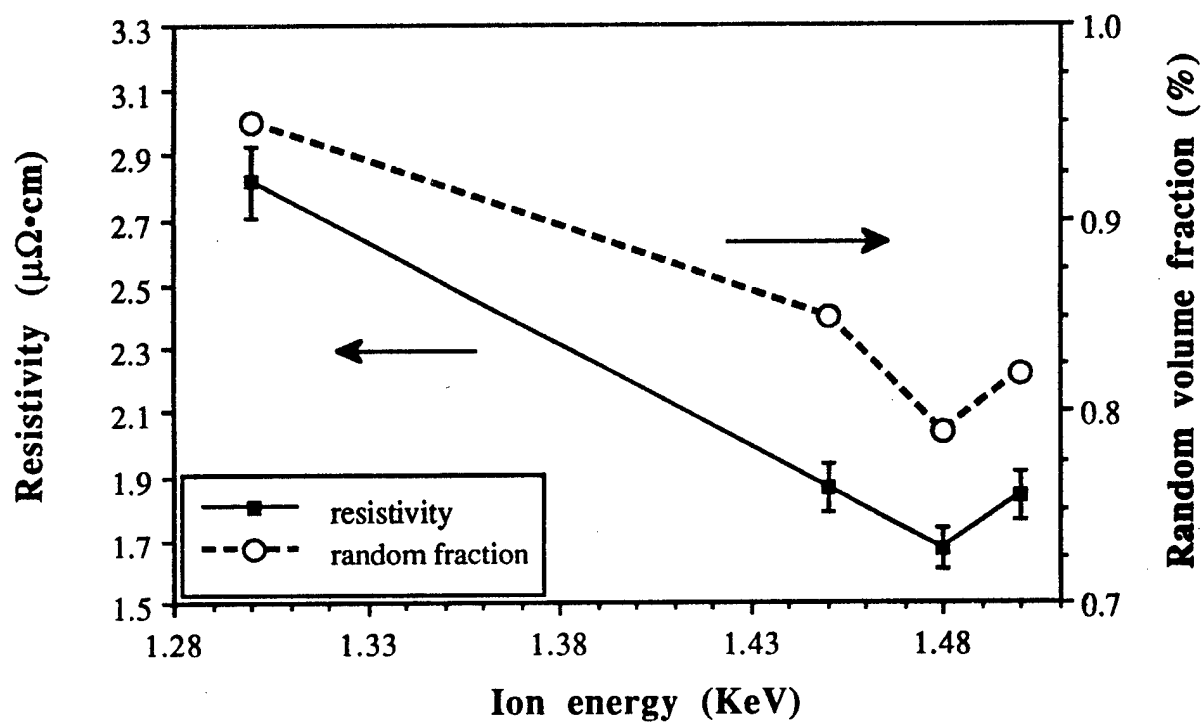
Figure 2. Resistivity and random volume fraction as a function of the ion energy used in the deposition of the silver films. Note the correlation in the minima of both curves.

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